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QUANTIFYING THE EFFECTS OF SOIL AND CLIMATE ON ABOVEGROUND BIOMASS PRODUCTION OF SALIX MIYABEANA SX67 IN QUEBEC

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Corresponding Author:	Nicolas Belanger, Ph.D. Université du Québec Montréal, CANADA
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Université du Québec
Corresponding Author's Secondary Institution:	
First Author:	Mario Fontana, Ph.D.
First Author Secondary Information:	
Order of Authors:	Mario Fontana, Ph.D.
	Michel Labrecque, Ph.D.
	Christian Messier, Ph.D.
	Francois Courchesne, Ph.D.
	Nicolas Belanger, Ph.D.
Order of Authors Secondary Information:	
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Abstract:	Soil and climatic conditions for optimizing aboveground biomass yields of bioenergy short rotation coppices (SRCs) of Salix are not well elucidated. The objective of this study was to identify and quantify the limitations induced by soil and climate, and compare the magnitude of their effects, on annual aboveground yields across ten SRCs of Salix miyabeana SX67 in Quebec, Canada. The effects of weather variation between years on yields were also tested within locations. In five plots per SRC, soil bulk density, particle size, exchangeable cations and bulk composition were analysed, and moisture deficits were estimated using leaf δ13C. For each location, numerous weather variables were simulated for spring, summer and the whole growing season. Climate was calculated by averaging weather variables for growing seasons for which annual yields were available. Annual aboveground biomass yields were modelled using linear regression, partitioning of the variance and mixed models with soil, weather and climate variables as predictors. Across SRCs, silt content, soil organic matter, pH, exchangeable Ca and Mg, and total N and Zn were significantly and positively related to aboveground yields (adj. R2 ranging from 0.38 to 0.79). Generally, annual yields were negatively related to summer temperature within SRCs (adj. R2 = 0.92) and drought across SRCs (adj. R2 = 0.54). Partitioning of the variance revealed that soil variables (80 %) had a greater effect on productivity than did climate variables (10 %). In fact, soil properties buffered or exacerbated water shortages and, thus, had a preponderant effect on yield.

Suggested Reviewers:	Brad Pinno, PhD Rsearch Scientist, Canadian Forest Service brad.pinno@canada.ca Dr. Pinno is a specialist on modeling tree growth. He has published many papers dealing with the influence of soil and climate on the productivity of fast growing tree species (e.g. populus).
	Simon Landhausser, PhD Professor and NSERC Chair, University of Alberta simon.landhausser@ualberta.ca Dr. Landhausser is a specialist of afforestation, namely forest land reclamation. He also has interest in environmental factor influencing forest establishment and growth.
	Andy Gordon, PhD Professor, University of Guelph agordon@uoguelph.ca Dr. Gordon is an agroforestry expert with a major focus on willow SRC. He is a soil scientist interested in nutrient cycling in forested systems.
	Naresh Thevathasan, PhD Research Manager and Adjunct Professor, University of Guelph nthevath@uoguelph.ca Dr. Thevathasan is an expert on willow SRC and nutrient cycling.
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QUANTIFYING THE EFFECTS OF SOIL AND CLIMATE ON ABOVEGROUND BIOMASS PRODUCTION OF *SALIX MIYABEANA* SX67 IN QUEBEC

Mario Fontana[1,2], Michel Labrecque[2], Christian Messier[1], François Courchesne[3], Nicolas Bélanger[1,4,*]

[1]Centre d'étude de la forêt, Université du Québec à Montréal, C.P. 8888, Succ. Centre-Ville, Montréal, Québec, H3C 3P8, Canada

[2]Institut de recherche en biologie végétale, Jardin botanique de Montréal, 4101 rue Sherbrooke est, Montréal, Québec, H1X 2B2, Canada

[3]Département de géographie, Université de Montréal, C.P. 6128, Succ. Centre-Ville, Montréal, Québec, H3C 3J7, Canada

[4]UER science et technologie, Téluq, Université du Québec, 5800 rue Saint-Denis, bureau 1105, Montréal, Québec H2S 3L5, Canada

*Corresponding author: nicolas.belanger@teluq.ca, Tel: 1 800 665-4333, Fax: 514 843-2160

Abstract

Soil and climatic conditions for optimizing aboveground biomass yields of bioenergy short rotation coppices (SRCs) of *Salix* are not well elucidated. The objective of this study was to identify and quantify the limitations induced by soil and climate, and compare the magnitude of their effects, on annual aboveground yields across ten SRCs of *Salix miyabeana* SX67 in Quebec, Canada. The effects of weather variation between years on yields were also tested within locations. In five plots per SRC, soil bulk density, particle size, exchangeable cations and bulk composition were analysed, and moisture deficits were estimated using leaf $\delta^{13}C$. For each location, numerous weather variables were simulated for spring, summer and the whole growing season. Climate was calculated by averaging weather variables for growing seasons for which annual yields were available. Annual aboveground biomass yields were modelled using linear regression, partitioning of the variance and mixed models with soil, weather and climate variables as predictors. Across SRCs, silt content, soil organic matter, pH, exchangeable Ca and Mg, and total N and Zn were significantly and positively related to aboveground yields (adj. R^2 ranging from 0.38 to 0.79). Generally, annual yields were negatively related to summer temperature within SRCs (adj. R^2 = 0.92) and drought across SRCs (adj. R^2 = 0.54). Partitioning of the variance revealed that soil variables (~80 %) had a greater effect on productivity than did climate variables (~10 %). In fact, soil properties buffered or exacerbated water shortages and, thus, had a preponderant effect on yield.

Keywords: soil nutrients, pedoclimatic models, water-use efficiency, site effect, farmland soils.

Introduction

Species of *Salix* (willow) can be used for numerous environmental applications, such as phytoremediation, soil stabilisation, and as noise barriers (Kuzovkina and Volk 2009). They are also grown in short rotation coppices (SRCs) as a means of generating bioenergy feedstocks and reducing the use of fossil fuels (Perttu 1999; Pacaldo et al. 2013). In southern Quebec, Canada, SRCs of *Salix* have been frequently established, given that they can achieve high yields and have the potential to improve abandoned farmland (Labrecque and Teodorescu 2003). However, defining optimal growing conditions for specific *Salix* cultivars is a major challenge for northern temperate zone nations (Tahvanainen and Rytkönen 1999). Sites with the highest potential for *Salix* growth in northern countries are poorly identified, in part, because *Salix* establishes successfully under a range of climates and soil conditions (Jørgensen and Blix 1985; Walker 1987; Pezeshki et al. 1998; Toillon et al. 2013). A given *Salix* cultivar can establish on sites with varying climates and soil conditions, but its growth rates can also vary greatly. For example, after three years of growth, aboveground biomass yields of basket willow or common osier (*Salix viminalis* L.) were 10 Mg ha^{-1} in southern Finland (Tahvanainen and Rytkönen 1999) and 70 Mg ha^{-1} in southern Quebec (Tahvanainen and Rytkönen 1999; Labrecque and Teodorescu 2003). Specific site conditions leading to optimal biomass yields of *Salix viminalis* and other *Salix* cultivars need to be identified to improve site selection for future SRCs of *Salix*.

Salix species have high N requirements compared to other fast-growing temperate species, including species within the genus *Populus* (Jug et al. 1999). *Salix* cultivars are also more sensitive to nutrient changes when grown in SRCs than under natural conditions (Weih 2001). Biomass yield of *Salix* is generally positively related to soil N availability and it responds well to fertilisation (Ericsson 1981a; Labrecque et al. 1998; Toillon et al. 2013). Phosphorus and K also increase aboveground biomass production of *Salix* under SRC (Ericsson 1981b; Adegbidi et al. 2001; Marler et al. 2001), but they are not systematically positively correlated with growth after fertilisation (e.g., Labrecque and Teodorescu 2003). Soil pH is positively related with *Salix* biomass yield, based on the performance of nine SRCs of purple osier (*Salix purpurea* L.) encompassing neutral to slightly alkaline soils in Canada (Ens et al. 2013). Root

development of *Salix viminalis* is inhibited in soils with pH values below 4, whereas growth increases following liming of acid soils (Hytönen 2005). The pH optima for *Salix* spp. growth slightly vary, depending upon authors (6 to 7, Mitchell et al. 1999; 5 to 8, Abrahamson et al. 2002; 5.5 to 7, Guidi et al. 2013a). Differences between these ranges may occur because *Salix* growth is also determined by other variables, including soil texture, soil nutrient availability and harvesting cycles. Further, *Salix* growth is generally higher in clayey soils compared to sandy soils (Labrecque and Teodorescu 2001; Toillon et al. 2013), but not for sites where clay content is very high (heavy clay; Guidi et al. 2013a). For clay content, the cutoff between positive (e.g., water content, physical protection of organic matter against microbes, high CEC) and negative (e.g., high bulk density restricting roots, low soil oxygen levels due to waterlogging) effects on *Salix* biomass yield is not well known. A few data are available for other genera within the Salicaceae family, but these do not necessarily equate to successful site selections for *Salix*. For a hybrid poplar clone Brooks6 (*Populus deltoides* × *P.x petrowskyana*) in central Alberta, for example, Pinno et al. (2010) suggested that waterlogging has being a major cause for growth declines in soils with clay contents greater than 60 %.

The effect of climate on *Salix* growth depends largely upon the regional context. Dry conditions frequently limit growth in low rainfall areas. For instance, in Denmark, soil moisture availability was reported as a major driver of *Salix* biomass yields, which were partly governed by rainfall (Larsen et al. 2015). Similar results for *Salix purpurea* were obtained on the Canadian Prairies (Ens et al. 2013). The relationship between water-use efficiency (WUE) and *Salix* biomass yield was also investigated. WUE can be estimated using $\delta^{13}C$ values of plant tissues (Farquhar et al. 1982). Under moisture deficiency, the rate of CO_2 inflow through stomata is decreased because of reduced stomatal aperture. This leads to higher WUE and less fractionation between ^{12}C and ^{13}C, which means a less negative $\delta^{13}C$ value. Conversely, more negative $\delta^{13}C$ values indicate more widely open stomata and a lower WUE. For six *Salix* genotypes that were cultivated on three sites in northern France, $\delta^{13}C$ was negatively related to biomass yield, suggesting that the most water-efficient genotypes were also the most productive (Toillon et al. 2013). Across three sites in central Saskatchewan, ,$\delta^{13}C$ values for Chinese or Miyabe willow (*Salix miyabeana*

Seemen) indicated that higher WUE led to greater biomass yields (Moukoumi et al. 2012). Ens et al. (2013) highlighted a similar relationship for *Salix purpurea* across a broad climatic gradient from western to eastern Canada, but two of their sites where water availability was very low did not follow the same trend. Finally, Schifman et al. (2012) showed small $\delta^{13}C$ variation in tree rings of various *Salix* cultivars, although cultivars showing the largest variation were more resistant (higher survival) to drier conditions, suggesting that WUE of these cultivars changed depending upon water availability. Such *Salix* cultivars likely present an advantage for SRC in the context of climate change and an increase during drought events.

Salix growth in northern North America and Europe is also largely limited by temperature. In Alaska, annual growth of Richardson's willow (*Salix lanata* ssp. *richardsonii* [Hooker] A.K. Skvortsov) was positively linked to temperature in mid-July and thawing degree-days (Walker 1987). In southern Finland, Tahvanainen and Rytkönen (1999) reported that biomass yield of ten *Salix* cultivars was negatively related to May and September air temperature, and positively related to October air temperature. In northern Sweden, Wijk (1986) reported that annual shoot increment of dwarf willow (*Salix herbacea* L.) varied by growing season length (which also influenced carbohydrate availability of the following growing season), whereas Sannervik et al. (2006) established a positive relationship between biomass yield of *Salix viminalis* and total radiation in southern Sweden.

Despite the establishment of a large number of SRCs in Quebec, studies linking *Salix* yields to soil and climatic conditions have not been conducted. The main objective of this paper was to identify and quantify soil and climatic factors that were limiting the growth of *Salix miyabeana* SX67 within and across ten SRCs in southern Quebec, Canada. Further, we compared the relative magnitude of limiting factors.

Material and method

Field sites and estimates of annual aboveground biomass

The study was conducted at ten SRCs in Quebec (Fig. 1), where *Salix miyabeana* SX67 was grown on various soils and under different climatic conditions (Tables 1, 2). Details about site histories and layout of these specific SRCs were provided by Fontana et al. (2016), who used a dendrochronological approach

to estimate annual aboveground biomass yields from growth rings and investigated the effects of coppicing and stool age on annual yields. The same annual yield estimates were used in the current study.

To estimate annual biomass yields, Fontana et al. (2016) used the largest stem diameter and dry biomass data that were previously obtained (i.e., between 2000 and 2013, but not systematically each year) from 24 to 36 healthy SX67 shrubs per SRC in 18 Quebec SRCs with different stem and root system ages. A strong linear relationship emerged between dry biomass and area of the largest stem (see Figure 2, Fontana et al. 2016). In each SRC that was investigated in the current study, extensive sampling of the largest stem was performed in five randomly selected plots (total of 50 plots, 5 × 5.4 m). Using dendrochronology, basal area increment was first quantified on the collected stems and then used as input to the equation for the linear relationship between dry biomass and area of the largest stems in order to backcast annual aboveground biomass yield (for full calculation details, see Fontana et al. 2016).

Means of annual yields were calculated from values that had been obtained from the five plots sampled at each SRC to obtain annual yields at the site scale. Once cuttings had been planted, a few growing seasons were needed for stools to fully establish and reach their maximum yield potential (MYP). Consequently, Fontana et al. (2016) drew inferences on productivity only for growing seasons that had reached MYP. The first growing season of subsequent rotations was excluded from statistical analyses because they were systematically lower than MYP. These annual yields were averaged within each SRC to produce a set of MYP values that could be used to model productivity across SRCs in the current study (Fig. 1). Because planting was performed in different years and the delay in reaching MYP appeared to be influenced by soil properties, the number of years that were used to compute MYP varied between SRCs (Fontana et al. 2016).

Soil sampling and analysis

A soil sample was collected at 0-25 cm and 25-50 cm depths in all fifty of the aforementioned plots. Samples were air-dried and then sieved to pass a 2-mm mesh. Soil particle size distribution was determined using a Laser Particle Analyser (Partica LA-950v2, Horiba Instruments, Irvine, CA, USA). To destroy soil organic matter prior to particle size analysis, samples from the BOI, MTL and SJPJ sites were

bleached twice with NaOCl (pH = 8, 1 h at 25 °C), centrifuged (400 rpm, 15 min) and washed with distilled water. Sesquioxides were removed after pre-treatment for organic matter; soil samples (5-10 g) were heated in citrate-bicarbonate solution (20 mL) with dithionite (0.8 g) using a double boiler (15 min at 75 °C) and centrifuged (400 rpm, 15 min) before and after washing with distilled water and acetone. Soil pH in water was measured electrometrically using a soil:solution ratio of 1:2 for mineral samples and 1:10 for organic samples. Organic matter and inorganic C ($CaCO_3$) contents were measured on all samples by loss-on-ignition in a muffle furnace at 575 °C (15 min) and 1000 °C (10 min), respectively (Rabenhorst 1988). Exchangeable Ca, Mg, Mn, K, Na, Fe, Al and Zn (hereafter, referred to as X_{exch}) were determined by atomic absorption/emission (model AA-555, Agilent Technologies, Santa Clara, CA, USA) after they were extracted using an unbuffered 0.1 M $BaCl_2$ solution (Hendershot et al. 2007). Total soil organic C and N (N_{tot}) were determined only on 0-25 cm depth samples using high temperature (1040 °C) combustion and thermal conductivity detection (EA1108 CNHS-O Analyzer, Thermo Fisons, Waltham, MA, USA). Except for ALB and BEL sites, bulk compositions (SiO_2, Al_2O_3, CaO, K_2O, MgO, MnO, Na_2O, P_2O_5, Fe_2O_3, Zn, TiO_2 and Ba) of all samples that were collected from the 0-25 cm depth were analysed by X-ray fluorescence spectrometry using a Philips PW2440 system (Panalytical, Almelo, The Netherlands) that was equipped with a Rhodium 60 kV end-window X-ray source, which operated at 3 kW. Fused beads were prepared from a 1:4 soil:lithium tetra(meta)borate mixture, which was heated for 18 min at 1000 °C. For BEL and ALB sites, bulk chemical composition was analysed using X-ray fluorescence spectrometry (S8 Tiger WD XRF, Bruker, Billerica, MA, USA), but the fused beads were prepared from a 1:10 soil:lithium tetra(meta)borate mixture. At three of the five plots within each SRC, undisturbed soil cores were collected in the interior rows at distances of 20, 40 and 60 cm from the shrubs. Sampling was performed at depths of 0-5, 20-25 and 40-45 cm (total of 270 samples) to develop shrinkage curves (Kohler-Milleret et al. 2013). Following this procedure, undisturbed soil samples were air-dried and apparent density was measured according to the plastic bag method (Boivin et al. 1990).

Weather conditions

The BioSIM model was used to simulate weather conditions for each SRC and growing season that was covered in the study. With inputs of site elevation, latitude and longitude, BioSIM uses multivariate regression to extrapolate data from the closest weather stations (Régnière 1996). Weather variables consisted of lowest temperatures, mean minimum temperatures (°C), mean temperatures (°C), mean maximum temperatures (°C), maximum temperatures (°C), degree-days (base 5°C), total solar radiation (MJ m^{-2}), precipitation (mm), mean number of days with precipitation, mean consecutive days with precipitation, highest values of consecutive days with precipitation, mean number of days without precipitation, mean consecutive days without precipitation, and highest values of consecutive days without precipitation. They were modelled using the three stations that were closest to each SRC: (1) for the beginning of April to the end of June, referred to as spring; (2) for July and August, referred to as summer; and (3) for the beginning of April to the end of November, referred to as seasonal. BioSIM yields weather data that are statistically indistinguishable from measured data (Régnière and Bolstad 1994). Weather variables were also averaged for all growing seasons that covered by MYP calculations. These are noted as climate variables.

Leaf sampling and analysis

In August 2011, leaves in the upper tier of the canopy were sampled on two adjacent and healthy stools in each of the five plots at seven of the ten SRCs, viz., ABI, BOI, LAV, MTL, RXP, SJPJ and STR (70 samples). Samples were oven-dried at 40 °C for at least 16 h. Thirty leaves per sample were weighed before they were finely ground (< 50 µm). Mean mass per leaf was calculated for each sample.

Total C concentration in leaves was determined using an elemental analyser (Vario Micro Cube, Elementar, Hanau, Germany), which was coupled with a Micromass isotope-ratio mass spectrometer (Isoprime 100, Isoprime, Cheadle, Cheshire, UK) in continuous flow mode to measure ^{12}C and ^{13}C. These isotopic C values were expressed as $\delta^{13}C$ ‰ with respect to the international standard Vienna Pee Dee Belemnite (V-PDB) using the following equation:

$$\delta^{13}\mathrm{C} = \frac{R_{sample}}{R_{standard}} - 1$$

with R_{sample} and $R_{standard}$ being the $^{13}C/^{12}C$ ratios of the sample and standard, respectively. To correct the raw data for inherent fractionation incurred by the analytical device, calibration was performed based on two laboratory reference materials that were normalised to NBS19-LSVEC for $\delta^{13}C$: urea (-42.16 ‰) and sucrose (-11.85 ‰). A third laboratory reference material, leucine (-28.75 ‰), was included with each batch sample that was run on the mass spectrometer to assess the accuracy of the calibration.

Statistical analysis

Datasets were arranged to allow statistical analyses at the site scale as well as at two temporal intervals. First, to quantify and compare the magnitude of effects of soil and climate on productivity across SRCs, MYP values were used with average soil and weather variables that were specific to each SRC and MYP year for each SRC (referred to as the site-scale dataset, n = 10). Secondly, to examine the effects of weather conditions on annual growth within a SRC and across SRCs, a dataset was constructed with all weather variables that were related to the annual yield values used to calculate MYP at each SRC (referred to as the inter-annual dataset, n = 30). Note that the BEL site was not included in the inter-annual dataset because data were available for only one growing season at this SRC.

The following statistical analyses were performed using R 3.01 (R Development Core Team 2012). ANOVA followed by Tukey's test were performed to compare weather variables of the 2010, 2011, 2012 and 2013 growing seasons between all possible pairs of years. A similar test was performed to compare weather variables between all possible pairs of SRCs using the growing seasons that were included in MYP calculations. For the 2011 growing season, water-use efficiency and water stress were investigated using foliar $\delta^{13}C$ values. Tukey's test was performed on plot-scale data between all possible pairs of SRCs to verify whether $\delta^{13}C$ significantly differed between SRCs ($P < 0.05$). To test for the effect of weather conditions on productivity within a SRC and across growing seasons, regression with forward selection was performed separately for each SRC. This allowed us to determine which weather variables best explained annual yields. Except for the LAV site (n = 6), the number of data points was too low to yield robust regression models. However, data were grouped for SRCs where weather variables were collinear. This allowed the construction of a mixed model with means of maximum summer temperatures and SRCs

(or sites) as fixed and random factors, respectively. Mixed-model analyses were performed using the function *lme*, which is available in the *nlme* package, because it is robust when modelling unbalanced designs (Laird and Ware 1982). The conditions of normality and homoskedasticity were graphically checked for all models.

To identify soil and climate variables that best explained MYP values across SRCs, forward selection was performed across SRCs. This was carried out using the function *forward.sel* in the *packfor* package. For the following soil variables, sand, silt and clay, organic matter, exchangeable soil nutrients and total bulk elements at 0-25 cm and 25-50 cm depths were multiplied by soil bulk density that had been estimated respectively at 0-5 cm and 40-45 cm depths to obtain volumetric concentrations. These were better predictors of productivity than mass concentrations, likely because they considered the soil volume that was explored by roots (rather than soil mass). Thus, only results that were obtained with volumetric concentrations are presented hereafter. Soil chemical properties at the RXP site (organic) were significantly different from those at all other SRCs (mineral), and the ABI site showed evidence of water shortages compared to other SRCs. In this SRC, $\delta^{13}C$ was an outlier, i.e., significantly less negative, compared to all other SRCs (see Results and Discussion). Therefore, various regression models were built with and without the RXP data for soil variables, and with and without the ABI data for climate variables. For greater insight into the effects of soil and climate on SX67 productivity, the variance of MYP was partitioned using soil and climate variables that best explained MYP (Peres-Neto et al. 2006).

Partitioning was performed using the function *varpart*, which is available in the *vegan* package (Peres-Neto et al. 2006). Models were also developed with and without the RXP and ABI sites due to their singular soil properties. For example, the RXP site was systematically omitted from models that included soil particle size and organic matter variables. Significance of variances that were explained only by soil or climate variables was tested by permutation through partial canonical redundancy analysis using the function *rda* available in the *vegan* package.

Results

Soil and climate conditions

The SRCs that were included in this study are characterised by heterogeneous soil conditions (Table 1). Soils from nine SRCs developed from mineral parent materials, whereas the soil at the RXP site developed from organic material. The RXP soil consequently has very high exchangeable Ca (Ca_{exch}) and organic matter content, and a dramatically low apparent bulk density (Table 1) compared to other SRCs. Soil pH across the SRCs ranges between 5.1 and 7.5. Coarser (sandiest) soils are generally the most acidic and have the highest Al_{exch} (Table 1). Soil P_2O_5 at the LAV site is the highest among the SRCs that were grown on mineral soils. Variability in precipitation and maximum summer temperature is mostly influenced by growing season rather than by SRC, whereas the opposite is observed for variables that were related to degree-days (5 °C) (Tables 2 & 3, Fig. 1). The ABI and ALB sites are the coldest, followed by the SJPJ and MTL sites. As a whole, climatic conditions are similar between the remaining six more southerly SRCs.

Site productivity as related to soil

Silt and Ca_{exch} at the shallower soil depth are the best proxies of productivity for the SRCs that were grown on mineral soils (thereby excluding the RXP site; Table 4). Mg_{exch} and Ca_{exch} are also significant indicators ($P \leq 0.05$) of productivity, regardless of parent material type. For SRCs grown on mineral soils, N_{tot}, organic matter, pH and total Zn at the shallower depth are positively related to productivity. At a depth of 25-50 cm, only Ca_{exch} is significantly linked to MYP (i.e., $P < 0.05$, adjusted $R^2 = 0.28$ and 0.38 for all SRCs and without RXP, respectively). The strengths of the relationships largely decrease when RXP data are included in the analysis.

Foliar $\delta^{13}C$ during the 2011 growing season

At the ABI site, foliar $\delta^{13}C$ during the 2011 growing season was significantly less negative than for all other SRCs (Fig. 2). The BOI and MTL sites also tended to have less negative values than the LAV, STR, SJPJ and RXP sites. Across SRCs, no relationship is found between annual yield of the 2011 growing season and foliar $\delta^{13}C$, regardless of whether data from the ABI and LAV sites are included or not (results not shown).

Site productivity as related to weather and climate

Across SRCs, MYP is significantly related to climate variables that are linked to drought: (1) total spring precipitation with (adjusted R^2 = 0.38, P < 0.5) and without (adjusted R^2 = 0.26, P < 0.1) ABI data; (2) seasonal highest value of consecutive days without precipitation, with (adjusted R^2 = 0.54, P < 0.01) and without (adjusted R^2 = 0.75, P < 0.01) ABI data; and (3) spring highest value of consecutive days without precipitation, with (adjusted R^2 = 0.56, P < 0.01) and without (adjusted R^2 = 0.70, P < 0.01) ABI data.

A series of significant relationships between weather variables and annual yields within SRCs were found, but only the most significant ones are reported here. At the LAV site, there is a negative relationship between the number of days with precipitation (i.e., from April to November) and annual yields (R^2 = 0.71, p < 0.01; results not shown). Conversely, significant relationships between annual yields and weather variables at other SRCs suggest negative (air temperature) and positive (precipitation) effects on annual growth. Nearly all variables that were related to temperature (e.g., degree-days, means of highest or lowest seasonal, spring or summer temperatures) and precipitation (e.g., seasonal, spring or summer precipitation, consecutive days without precipitation, consecutive days with precipitation) were significant (P < 0.05) using mixed models for all SRCs, except the LAV site (results not shown). The most significant weather variable was the mean of maximum summer temperatures (R^2 = 0.92, P < 0.01; results not shown), which was negatively related to annual yields.

Pedoclimatic models of productivity

The variance in MYP is successfully partitioned using soil (i.e., silt and Ca_{exch}) and climate (i.e., spring drought) as explanatory variables. These are the most robust soil and climate responses that were detected. A strong collinearity between the two variables is present (Table 5). In all cases, each variable explained a significant part of the variance that was not explained by the other variable.

Discussion

Soil variables as related to yield

Soil pH, organic matter, Mg_{exch}, Ca_{exch}, Zn_{tot} and silt were all positively related to MYP, with silt exhibiting the highest R^2 (Table 4). These soil variables were also collinearly related across the SRCs grown on mineral soils (results not shown). Soil N was linearly related to biomass yields, as has been

reported in many other studies on willow (Ericsson 1981a; Ens et al. 2013; Toillon et al. 2013; Larsen et al. 2016). For *Salix purpurea*, Ens et al. (2013) reported that the most productive sites had a silt content ranging from 40 to 60 %, which is equivalent to a loamy soil. Similarly, Guidi et al. (2013a) suggested that loamy soils are ideal for optimal *Salix* productivity. The structured nature of loamy soils apparently favours gas and water flow while ensuring water retention (Pachepsky et al. 2001). Tahvanainen and Rytkönen (1999) found that productivity of *Salix viminalis* was decreased on coarse-textured (sandy) soils or heavy compacted clays. Clay content was also significantly ($P < 0.001$) related to dry biomass production across a climatic gradient of five *Salix* plantations that had been established on coarse sand and loamy sand soil types in Denmark (Larsen et al. 2014). In our study, sand and clay contents poorly explained the MYP data. Yet, soil texture is clearly a relevant proxy for forecasting *Salix* productivity (Nord-Larsen et al. 2015), but indicators seem to vary from one context to another.

The reliability of soil Ca_{exch} by volume as a proxy to estimate growth was robust, regardless of whether the data from the RXP site were included or omitted from the analysis (Table 4). The data were of the same order of magnitude as other SRCs, given that low soil bulk density at the RXP site corrected for the high Ca_{exch} mass concentration (Table 1). The high acidity of some of the study soils, which were formerly forest soils with pH values approaching 5.0, results in high soil exchangeable Al_{exch} saturation and, thus, much lower Ca_{exch} concentrations (Table 1). As was the case of the study by Ens et al. (2013) for *Salix purpurea*, we found that chemical properties in the uppermost part of the soil profile best explained productivity across SRCs. This is probably because fine roots of *Salix* are generally concentrated within the uppermost 10 cm of soil (Heinsoo et al. 2009; Jerbi et al. 2015). Ens et al. (2013) also found a very strong positive relationship between yields and soil Ca_{exch} concentrations, although the relationship was stronger with total CaO content and pH, indicating a significant influence of the nature of the parent material (e.g., acid-base status) on growth.

Soil Mg_{exch} also explained at least 42 % of the variation in *Salix* growth, regardless of whether the data from the RXP site were included or omitted from the analysis (Table 4). Although Mg is an essential nutrient (Ericsson 1981b), no study has reported, to our knowledge, a positive relationship between soil

Mg_{exch} and yields of *Salix*. This positive relationship is likely explained by the fact that less productive SRCs have both high sand content and low Mg_{exch} (Table 1). The SRCs grown on sandy soils (i.e., LAV, MTL and STR) were also characterised by low soil pH. In the range of soil pH values that were determined in this current study (5.15 to 7.51, Table 1), both nitrification rates and base cation availability can increase significantly with increasing pH (Havlin et al. 2005), while solubility of trace metals such as Zn or Mn can decrease (Sanders 1983; Martínez and Motto 2000). Optimum pH ranges were often assessed for *Salix* spp., but these have varied between studies (Mitchell et al. 1999; Abrahamson et al. 2002; Guidi et al. 2013a). With our data, it is difficult to set minimum and maximum pH thresholds because the SJPJ and RXP sites were among the most productive SRCs and had relatively low pH values (5.3 and 5.5, respectively), meaning that soil pH had no direct effect on SX 67 growth.

Factors limiting yield at low productivity SRCs

In SRCs that were grown on sandy soils, i.e., LAV, MTL and STR, soil nutrient availability was generally low, e.g., total N and Ca_{exch} (Table 1). This likely explained the low MYP on the MTL site. At the STR site, we suspected that the Ap horizon had been depleted of organic C (and thus, organo-mineral complexes) due to a history of intensive farming and tilling, which can decrease soil structural stability (e.g., Lipiec and Stępniewski 1995). A preliminary analysis of three soil profiles in the adjoining grass strips, which were not cultivated or at least not as intensively as in the past (as indicated by the absence of a plough pan), confirmed our hypothesis. Clay, organic matter, Ca_{exch} and Mg_{exch} levels, and pH were dramatically higher in the A horizon of the grass strips (+118 %, 57 %, 45 %, 106 % and 20%, respectively) compared to that of the cultivated soil (Fontana 2016).

Repeated tilling has been reported to increase bulk density to a depth of 40 cm in clay loam and sandy loam soils, which can strongly impede the productivity of *Salix viminalis* during the first growing season (Souch et al. 2004). In subsequent years, an increase in growth was observed, most likely because the root system had developed beyond the compacted layer (up to a depth of 2 m). At the ABI site, a plough pan at a depth of about 20 cm (Table 1) was evidence of soil compaction, which had appeared to have completely restricted root development beyond that depth. Consequently, ABI was the only SRC for

which soil bulk density at 0-5 cm increased in the interior rows with increasing distance from the shrubs. Overall, bulk density increased by 7.3 % when moving from 20 cm to 60 cm away from the shrubs (not shown). Thus, the roots were constrained to a shallower soil volume for nutrient exploration and acquisition. This increased the sensitivity of the root system to drought, as seen by less negative foliar $\delta^{13}C$ values, indicating a greater water deficit at the ABI site during the 2011 growing season, despite it being a relatively high rainfall year (Table 3). Low MYP at the ABI site, therefore, was likely induced by soil compaction, which eventually led to a smaller soil volume for roots to explore and exploit (resulting in water deficits). For this reason, it was decided to model SX67 yields without the ABI data (Table 5). Martin and Stephens (2006) proposed that increasing soil bulk density decreased the yield of *Salix viminalis* as waterlogging was induced by low soil aeration. Establishing SRCs of *Salix* at sites where conventional tillage was performed on a yearly basis, especially on clayey soils, was likewise a situation to be avoided as this can decrease nutrient and water availability, as well as microbial biomass (Gadermaier et al. 2012; Fontana et al. 2015). Former agricultural land may create restrictions for optimal *Salix* growth; therefore, it was been suggested that plough pans be mechanically destroyed prior to SRC establishment (Borghei et al. 2008). In turn, *Salix* root development could restore some structure to the soil, as has been observed with black alder (*Alnus glutinosa* [L.] Gaertn.) plantings (Meyer et al. 2014).

Water stress across growing seasons and SRCs

In high-latitude forest systems, air temperature is generally positively linked to productivity when soil moisture is sufficient, but the relationship can become negative under increasing water deficits (D'Arrigo et al. 2008). At the LAV site, the negative relationship between annual yields and precipitation, which followed roughly the same pattern of annual fluctuation as seasonal degree-days (Table 3), suggests that this SRC did not experience moisture limitation. This is likely because the sandy loam soil at the LAV site permitted the development of a deep rooting system, which reached at least 70 cm (M. Fontana, *personal observation*). The occurrence of a perched water table or poor water infiltration at many points in time during the growing season was evident from pooled water at the soil surface, thereby reflecting recurring periods of high soil moisture (M. Fontana, *personal observation*). Similarly, there was no indication of

water shortage in Svalbard, Norway, as the growth of polar willow (*Salix polaris* Wahlenb.) was negatively correlated with summer precipitation (Buchwal et al. 2013). Buchwal et al. (2013) argued that the negative effect of rainfall on polar willow growth was probably due to a concomitant decrease in air temperature and solar radiation. In the current study, summer precipitation and air temperature at the LAV site were similar to that of the BOI site; however, foliar $\delta^{13}C$ was more negative (but not statistically different) at the LAV site compared to the BOI site (Fig. 2). These results likely highlight the influence of soil type on WUE and water stress (Martin and Stephens 2006; Moukoumi et al. 2012).

With the exception of the LAV site, annual yields within SRCs were negatively affected by the means of maximum summer temperatures. Increased maximum summer temperatures likely triggered more frequent episodes of water stress by increasing evapotranspiration. Such episodes have been linked to declines in tree growth in Quebec (Payette et al. 1996; Wheaton et al. 2008). Similarly, Guidi Nissim et al. (2013b) suggested that coupling of relatively low seasonal rainfall and high air temperature was responsible for low annual yields of various *Salix* cultivars in southern Quebec. Sevel et al. (2012) observed higher yields of four *Salix* cultivars on sand compared to organic soil for a given year in Denmark, whereas the opposite was observed the following year. Yields on these sites could have varied due to changes in soil water status.

In our study, no relationship was found between annual yields in 2011 and $\delta^{13}C$, regardless of whether data from the ABI and LAV sites were omitted or not from the analysis (results not shown). With the exception of the ABI site, water stress was apparently not sufficiently large to limit productivity significantly across SRCs. For the 2011 growing season, summer precipitation significantly affected $\delta^{13}C$ (adjusted $R^2 = 0.92$, $P < 0.01$) across SRCs when the ABI and LAV data were removed from the regression analysis (results not shown). The 2011 growing season was among the wettest that was measured (Table 3), whereas biomass yields may have been more strongly affected by lower water supply during the driest growing seasons (e.g., 2012). Nevertheless, when weather variables were averaged on an annual basis (i.e., to test for a climate effect), spring drought partly limited productivity (Table 5).

Comparison of soil and climate effects on biomass yields

Despite the strong gradient in degree-days between northern and southern SRCs (Table 2), no relationship between this variable and yield was detected across SRCs. One of the two northernmost SRCs was among the least productive (i.e., ABI), whereas the second was among the most productive (i.e., ALB). In contrast, along a latitudinal transect in the Clay Belt of Quebec, Lapointe-Garant et al. (2010) found that seasonal degree-days was the only climatic variable with sufficiently large variation across sites to influence the growth of trembling aspen (*Populus tremuloides* Michx.) stands. Although no information was provided in the aforementioned authors' study, it is suspected that their soils were more homogeneous and climate was more heterogeneous than was observed in the current study. In this regard, six of the ten SRCs in the current study are located close to one another and had similar climates, whereas the soil properties within these six SRCs were quite different.

Annual yields of SX67 within SRCs and across growing seasons were only influenced by weather conditions and varied by up to 44 % (Table 2). In contrast, MYP values across SRCs varied by as much as 380 % (data not shown) and were influenced by both soil and climate. Since the timing of drought that limited yields across SRCs significantly differed between years and not between SRCs (Tables 2 & 3), we speculate that soil was a more important factor limiting SX67 growth compared to the effects of climate. Except for severe drought conditions that are routinely incurred under Mediterranean climate conditions (Bergante et al. 2010), the soil has generally a stronger affect on the productivity of *Salix* than does climate, even across a large climatic gradient (Weih 2004; Ens et al. 2013). When quantitatively confronting the effects of climate and soil, we found a strong collinearity between silt content and the frequency of drought episodes (Table 5). This is because soils with unfavourable growing conditions were among the driest (i.e., ABI, MTL), whereas those with optimal growing conditions (i.e., BEL, HTG, SJPJ) had the greatest moisture levels (Table 2). When including or omitting the data from the ABI and RXP sites, spring drought explained between 10 and 14 % of the variation in yields that was not explained by silt content. Therefore, it would appear more realistic and unbiased to consider only this fraction as the effect of climate on yields instead of the whole climate effect (i.e., including collinearity, Table 5).

Conclusion

Within each of the SRCs that we studied, different factors limited aboveground biomass yields of *Salix miyabeana* SX67. Soil nutritional balances and soil physical properties, which were likely influenced by past agricultural practices, appeared as significant factors. To estimate the maximum potential biomass yield of a SRC, silt content was a reliable indicator as it supports high cation exchange capacity without placing the same mechanical constraints on root growth that are imposed by clayey soils, especially those that have been compacted by tillage. Soil exchangeable Ca concentration was identified as an important limiting factor, likely due to the acidic nature of the soils under study. Both these soil variables appeared to be major drivers of biomass yields compared to climate variables. This is attributable to the greater heterogeneity of soils compared to that of climate in southern Quebec, and to the experimental design. Nevertheless, this study confirms that water supply limits productivity in this area. Under a warming climate, evapotranspiration rates and, therefore, water deficits should increase in southern Quebec. An increase in soil organic C content, which was also shown to be a positive factor for biomass yields, could alleviate some of the water shortages under changing climate. Proper care should be taken at all stages of SRC management to optimise soil organic matter and hydro-structural properties.

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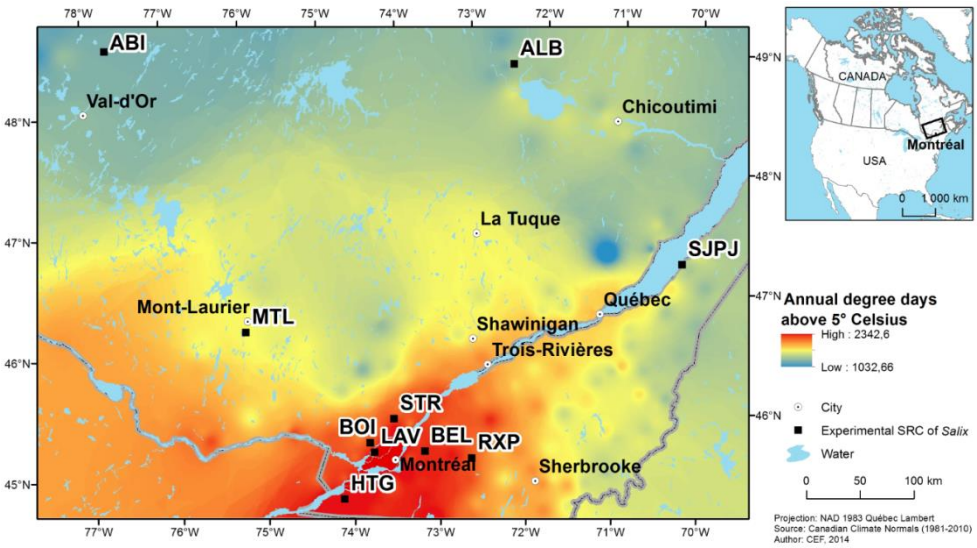

Fig. 1 Location of the ten willow SRCs in southern Quebec and simulated mean annual degree-days above 5°C in the study area using BioSIM (Régnière 1996)

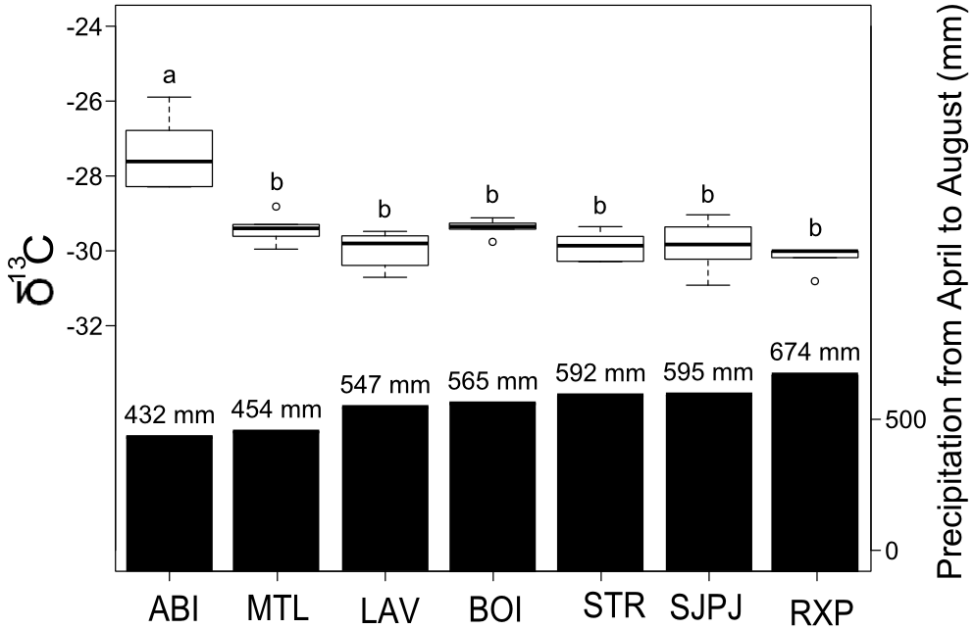

Fig. 2 Mean foliar $\delta^{13}C$ (boxes) and precipitation from April to August (bars) measured at each SRC during the 2011 growing season. Different letters were assigned when a significant mean difference ($p<0.05$) was found between SRCs

Table 1 Soil particle size distribution and chemical properties at the 0-25 cm depth, and dry bulk density at the 0-5, 20-25 and 40-45 cm depths at each of the ten SRCs

Site	Particle size			Total N, P and Zn						Exchangeable cations					Dry bulk density		
	Sand	Silt	Clay	N_{tot}	P_2O_5	Zn_{Ox}	†O.M.	pH	£C:N	Ca_{exch}	Mg_{exch}	K_{exch}	Mn_{exch}	Al_{exch}	0-5	20-25	40-45
	——%——			—g kg^{-1}—		ppm	–%–			——cmolc kg^{-1}——					——g cm^{-3}——		
ABI	19.4	37.5	43.1	2.4	1.3	92.8	7.9	5.64	19	9.64	3.99	0.98	0.05	0.66	1.13	1.62	1.65
ALB	32.2	58.2	9.6	2.0	2.3	85.8	10.2	6.21	30	13.97	3.31	1.46	0.00	0.00	1.42	1.50	1.49
BEL	34.5	52.7	12.8	2.5	1.9	108	9.1	6.88	21	24.21	6.72	0.70	0.01	0.00	1.50	1.56	1.48
BOI	34.9	46.2	18.9	3.4	2.4	117.8	9.2	7.51	16	17.45	5.02	1.20	0.01	0.06	1.31	1.45	1.56
HTG	18.9	53.5	27.6	3.4	2.2	103.6	11.2	7.30	19	28.54	8.85	0.60	0.01	0.02	1.25	1.53	1.64
LAV	49.6	39.1	11.3	2.0	3.9	62.6	5.4	5.27	16	3.14	0.20	1.71	0.02	1.15	1.20	1.45	1.41
MTL	74.1	22.1	3.7	1.7	1.7	56.2	6.9	5.15	24	1.33	0.08	0.19	0.04	1.73	1.15	1.39	1.42
RXP	46.2	48.1	5.7	19.0	17.8	287	67.6	5.54	21	63.40	2.19	0.53	0.08	1.72	0.55	0.56	0.41
SJPJ	n.a.	n.a.	n.a.	3.1	1.9	93.6	9.1	5.30	17	9.74	0.63	0.52	0.06	1.26	1.43	1.62	1.72
STR	59.2	32.1	8.7	1.7	1.6	49.4	4.6	5.60	16	5.14	0.78	0.69	0.02	0.34	1.47	1.68	1.71

† O.M. is organic matter, whereas $_{exch}$, $_{tot}$ and $_{Ox}$ refer to exchangeable, total and oxide, respectively
£ C:N was computed as O.M. to N_{tot} ratio divided by 1.724 (Nelson and Sommers 1996)
Soil particle size distribution at the RXP site is not applicable (n.a.) because it is mostly organic

Table 2 Climate variables and maximum yield potential (MYP) for each of the ten SRCs

Site	Precipitation (mm)		†Drought (days)		Mean of maximum temperature (°C)	Degree-Days (°C base 5)	‡Years used for MYP	Calculated MYP (Mg ha^{-1} year^{-1})
	£Spring	£Summer	£Spring	£Seasonal	£Summer	£Seasonal		
ABI	226 (17%) a	188 (10%) a	9.3 (12%) a	10.3 (15%) a	23.2 (2%) a	1609 (4%) a	2011 to 2013	9.0 (11%)
ALB	253 (14%) a	155 (4%) a	10.5 (61%) a	11.5 (43%) a	24.0 (1%) ab	1661 (5%) a	2012 to 2013	20.1 (1%)
BEL	318	185	7	8	26.1	2265	2013	28.0
BOI	289 (20%) a	177 (10%) a	9.25 (15%) a	10 (10%) a	26.6 (2%) c	2358 (3%) c	2010 to 2013	18.6 (22%)
HTG	324 (22%) a	178 (25%) a	9 (22%) a	10 (10%) a	26.9 (3%) c	2414 (3%) c	2011 to 2013	24.7 (39%)
LAV	278 (22%) a	178 (21%) a	10.5 (29%) a	12.5 (33%) a	26.6 (2%) c	2477 (3%) c	2008 to 2013	13.1 (28%)
MTL	233 (31%) a	186 (11%) a	12.3 (51%) a	13 (41%) a	25.4 (2%) b	2049 (5%) b	2010 to 2013	6.5 (44%)
RXP	340 (19%) a	219 (37%) a	8.6 (18%) a	11 (24%) a	26.3 (2%) c	2333 (3%) c	2010 to 2013	15.2 (24%)
SJPJ	323 (28%) a	218 (22%) a	7.5 (28%) a	10 (14%) a	24.2 (0%) ab	1817 (2%) ab	2011 and 2013	21.3 (13%)
STR	298 (24%) a	214 (18%) a	10.5 (61%) a	12 (35%) a	26.9 (1%) c	2313 (0%) c	2010, 2011	9.6 (4%)

Climate variables are simulated with the BioSIM model (Régnière 1996). Means are computed specifically for the years used for calculating MYP
MYP values were calculated by Fontana et al. (2016)
The coefficients of variation are indicated in parentheses
Significant differences in climate variables ($P < 0.05$, t-test) between SRCs and growing seasons are indicated within a column by different letters
† Refers to the highest value of consecutive days without precipitation
‡ Indicates the growing seasons used to calculate site MYP
£ Spring, summer and seasonal respectively refer to the means for April to June, July to August and April to November

Table 3 Climate variables for each growing season studied

Year	Precipitation		Drought†		Maximum temperature	Degree-Days
	£Seasonal (Days)	£Summer (mm)	£Spring (days)	£Seasonal (days)	£Summer (°C)	£Seasonal (°C base 5)
2010	95 (10%) a	176 (23%) a	14 (10%) a	14.0 (10%) a	33.0 (3%) a	2161 (14%) a
2011	93 (7%) a	231 (19%) b	7.8 (21%) b	10.1 (14%) bc	31.5 (6%) bc	2190 (15%) a
2012	78 (13%) b	150 (16%) a	10.8 (34%) a	13.8 (25%) ab	32.7 (2%) ab	2193 (15%) a
2013	95 (10%) a	181 (14%) a	8.5 (14%) b	8.8 (7%) c	30.9 (2%) c	2051 (15%) a

Climate variables are simulated with the BioSIM model (Régnière 1996). Means are computed from the ten SRCs
The coefficients of variation are indicated in parentheses
Significant differences ($P < 0.05$, t-test) between SRCs and growing seasons are indicated within a column by different letters
£Spring, summer and seasonal respectively refer to the means for April to June, July to August and April to November
†Drought refers to the highest number of days without precipitation

Table 4 Significant linear regressions between volumetric soil properties and maximum yield potential (MYP) across the ten SRCs

Soil variables	Depth: 0-25 cm	
	Adj. R^2 (*n* = 10)	**Adj. R^2 (*n* = 9)**
Silt	n.a.	(+) 0.79***
Clay	n.a.	(+) 0.00
Sand	n.a.	(-) 0.15
C_{org}	(+) 0.00	(+) 0.71**
N_{tot}	(+) 0.00	(+) 0.54*
C_{org}/N_{tot}	(+) 0.00	(+) 0.00
P_2O_5	(+) 0.00	(+) 0.00
Zn_{tot}	(+) 0.54**	(+) 0.70**
K_{exch}	(+) 0.00	(+) 0.00
Ca_{exch}	(+) 0.56**	(+) 0.78**
Mg_{exch}	(+) 0.42*	(+) 0.48*
Al_{exch}	(-) 0.22$^{(*)}$	(-) 0.20
pH	(+) 0.39*	(+) 0.38*

For $n = 9$, models were performed without the RXP data
Linear models are significant at $P \leq 0.1$ (*), $P \leq 0.05$ (*), $P \leq 0.01$ (**) or $P \leq 0.001$ (***)
n.a. is not applicable
$_{exch}$ and $_{tot}$ refer to exchangeable and total, respectively
C_{org} is organic carbon

Table 5 Partitioning of the variance of maximum yield potential (MYP) between spring drought, expressed as the average of the highest number of consecutive days without precipitation between April and June, and soil quality, either expressed by exchangeable Ca (Ca_{exch}) or silt volumetric content

Soil variable	*n*	Adj. R^2 of the soil variable ∁ spring drought	Adj. R^2 of the soil variable ∩ spring drought	Adj. R^2 of spring drought ∁ soil variable	Adj. R^2
Ca_{exch}	10	$0.14^{(*)}$	0.42	$0.14^{(*)}$	
Ca_{exch}	8	0.21^{**}	0.59	0.10^{*}	
Silt	9	0.29^{**}	0.50	0.05	
Silt	8	0.18^{*}	0.59	$0.10^{(*)}$	

All linear relationships are positive. Models are significant at $P < 0.1(^{(*)})$, $P < 0.05(^{*})$ or $P < 0.01(^{**})$. The column entitled Adj. R^2 of the area of largest diameter ∁ spring drought indicates the adjusted R^2 of the variance explained by the soil variable which does not overlap the effect of spring drought. The column entitled Adj. R^2 of the soil variable ∩ spring drought indicates the adjusted R^2 of the variance explained by both the soil variable and spring drought. The column entitled Adj. R^2 of the spring drought ∁ soil variable indicates the adjusted R^2 of the variance explained by spring drought which does not overlap the effect of the soil variable. The column entitled Adj. R^2 indicates the adjusted R^2 of the variance explained by the cumulative effect of spring drought and the soil variable. For $n = 10$, all SRCs were used for modeling, whereas the RXP site (i.e. the only site with organic soil) was removed for $n = 9$, and the RXP and ABI sites (i.e. site with water stress compared to other sites) were removed for $n = 8$